NEXUS
RESEARCH LABORATORY, INC.

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Revision A

AN INTRODUCTORY LABORATORY MANUAL OF OPERATIONAL AMPLIFIER EXPERIMENTS

INTRODUCTION

The entire concept of feedback theory, particularly in the field of operational amplifier technology, has become increasingly more important to the electronic design engineer. Today's design trend is to utilize the operational amplifier as the fundamental "analog building block" when designing the multitude of basic active circuits which comprise our complex modern day electronic systems.

In an endeavor to indoctrinate the engineering student into the field of operational amplifier techniques, the attached collection of "Ten Basic Illustrative Examples of Operational Amplifier Connections" has been written as a guide toward setting up and/or performing a series of orientation-type laboratory experiments.

The first two examples are intended to illustrate the basic performance of an "ideal" operational amplifier. Circuits #3 and #4 introduce the concept of input error voltage. Circuit #5 illustrates equivalent input offset voltage, and circuit #6 illustrates the effect of input offset current. Circuits #7, #8, and #9 demonstrate applications which are possible with a differential input type of operational amplifier, and circuit #10 is included because of the great importance of the operational integrator to system designers.

The diagrams include information about the basic requirements of the various test instruments which have to be used in order to measure amplifier performance in these investigations. Naturally, there is considerable room for test equipment substitution. While many of the component tolerances are specified to ±1%, suitable substitutions may be made depending upon the degree of accuracy which the experimenter may want to achieve, and also, by the availability of components in each laboratory setup.

Most of the illustrations are described in a rather general fashion. Exact values and procedures have not been described in detail because the examples are intended to be used only as a guide and not as a student's "cookbook."

DEFINITIONS

An "ideal" amplifier is defined as one having infinite open loop gain, infinite input impedance, infinite bandwidth, zero output impedance, zero offset voltage and zero offset current.

The indicated direction of all currents is in accordance with current flow convention, NOT electron flow convention.

Open loop gain, A_o, is considered to be a positive ratio in all of these examples because the absolute value of A_o was used in the derivation of the equations.

OFFSET VOLTAGE ZERO ADJUSTMENT

For maximum accuracy the offset voltage should be adjusted to establish a zero output prior to making an actual measurement. This control is generally indicated on schematic drawings as the "E_{os} Zero Adj."

In practice, the input signal(s) are replaced with a short-circuit-to-ground and the E_{os} trim pot is adjusted for a zero amplifier output, as monitored with a suitable meter.

Additional information about offset voltage and the various zeroing techniques may be found in Reference #2, Nexus Application Note, APP-1c.

LIST OF REQUIRED TEST EQUIPMENT

In addition to one Nexus type SQ-10a operational amplifier and one type NSK-7 mating socket, the following test equipment is required in order to properly conduct the various experiments which are outlined:

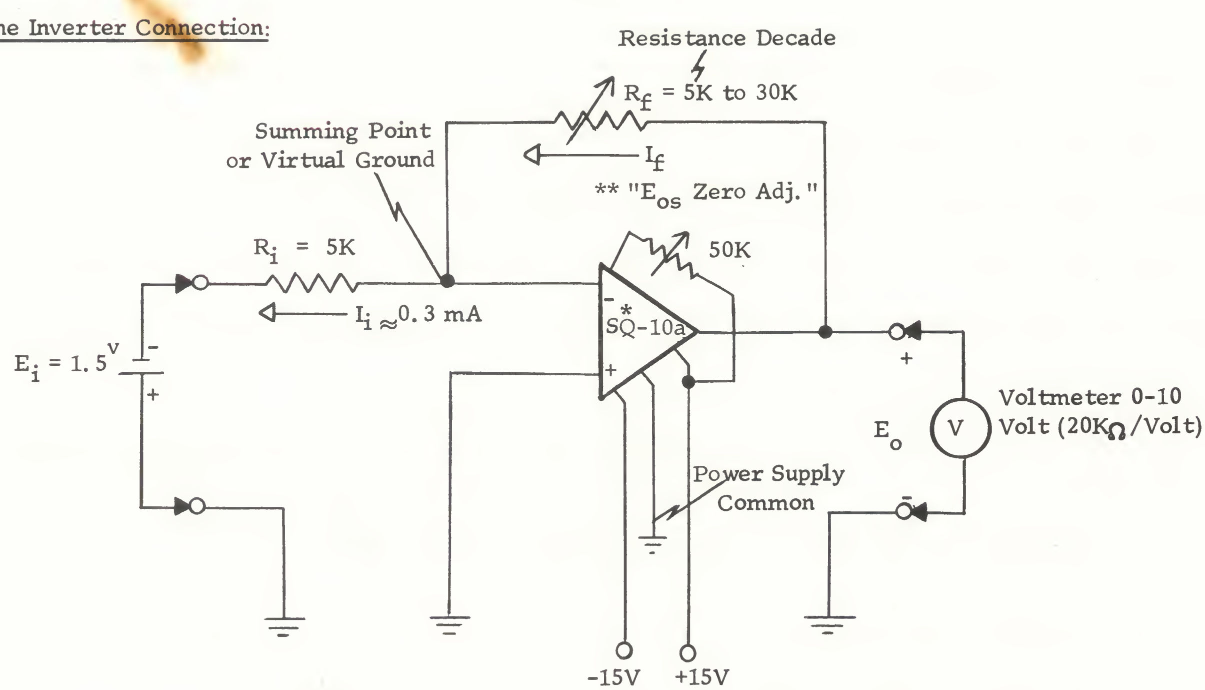
1. One dual power supply with at least 0.1% regulation to operate the operational amplifier (±15 volts at 30mA for the Nexus type SQ-10a).
2. One resistance decade, 0 to 100k Ω in 10 Ω steps, ±1%, 1 watt, 5mA rating.
3. One shielded resistance decade, 0 to 100k Ω in 10 Ω steps, ±1%, 1 watt, 5mA rating.
4. One digital voltmeter, 10 volts full scale range with 1mV resolution OR an equivalent type potentiometric voltmeter.
5. One 0 to 3 volt precision voltage source with 1mV resolution and source resistance less than 100 Ω.
6. One multirange dc microvoltmeter, 500-0-500 μV full scale to 10-0-10 volts full scale, accuracy ±5%, input resistance greater than 100k Ω. The VTVM section of many potentiometric voltmeters will suffice very nicely for the above measurement requirements.
7. One multimeter to measure 0 to 10 volts dc (20k Ω/volt) and 0 to 1mA with an accuracy of ±2%.
8. One strip chart recorder with 0-10 volt full scale input sensitivity and input resistance greater than 100k Ω OR one oscilloscope with a 2 second/cm time base.

The following electronic hardware is also necessary:

1. One 50kΩ, 10-turn potentiometer
2. One 100kΩ, 10-turn potentiometer
3. One 2kΩ, 2-watt potentiometer
4. One 10Ω, 1-watt, 1% resistor
5. One 100Ω, 1-watt, 1% resistor
6. Two 2kΩ, 1-watt, 1% resistor
7. One 5kΩ, 1-watt, 1% resistor
8. One 7.5kΩ, 1-watt, 1% resistor
9. One 9.1kΩ, 1-watt, 1% resistor
10. One 10kΩ, 1-watt, 1% resistor
11. Two 20kΩ, 1-watt, 1% resistor
12. One 30kΩ, 1-watt, 1% resistor
13. Two 1MΩ, 1-watt, 1% resistor
14. One 22Ω, 1/4-watt, 10% resistor
15. One 100MΩ, 1/4-watt, 10% resistor
16. Two 100pF ceramic capacitors
17. One 220pF ceramic capacitor
18. One 500pF variable mica capacitor (Elmenco/Arco #4610 or equivalent)
19. One 1mfd/50 volt metallized mylar or paper, or equivalent low leakage capacitor
20. Two normally closed push button switches
21. Two normally open push button switches
22. One 1-pole, three-position rotary switch, shorting or non-shorting
23. A wide mouth thermos bottle, or equivalent thermally isolated enclosure
24. One 1.5 volt "D" cell or equivalent
25. Two 3-volt batteries (5mA current drain)

TEN BASIC ILLUSTRATIVE EXAMPLES OF OPERATIONAL AMPLIFIER CONNECTIONS

I **The Inverter Connection:**



1. The Input Current, $I_i \approx \frac{E_i}{R_i} = \frac{-1.5V}{5k} = -300\,\mu A$
2. The Feedback Current, $I_f \approx I_i$
3. The output voltage, $E_o \approx -(I_i)(R_f) = -(-300\,\mu A)(R_f)$. For the I_i and R_f values shown, E_o could be set to any voltage between 1.5 and 9 volts.
4.

$E_o \approx -\frac{R_f}{R_i} E_i$	Also, $E_o = -(I_f)(R_f)$

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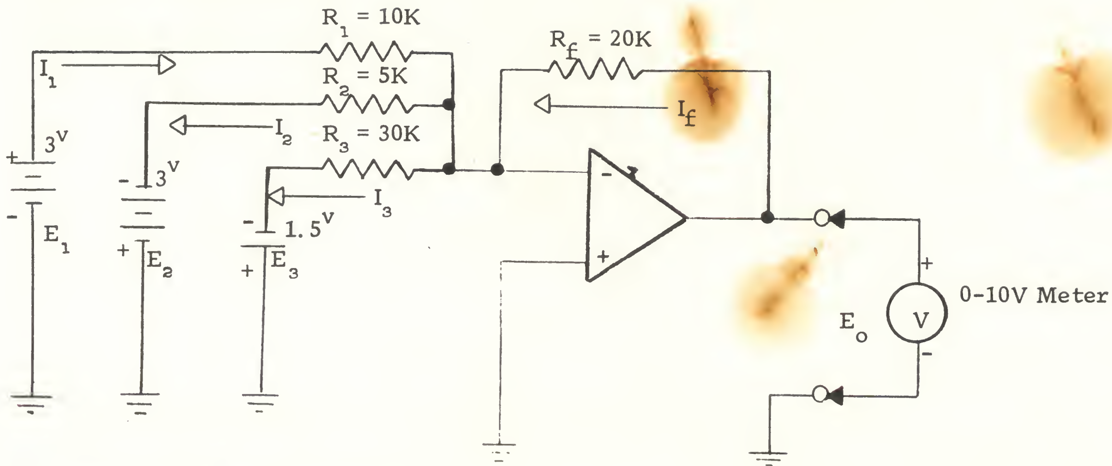
*Type SQ-10a operational amplifier is a product of Nexus Research Laboratory, Inc., Canton, Massachusetts, U.S.A. For detailed technical information, please refer to data sheet PB-103a-9/66.

**The "E_{os} Zero Adj." trim pot and power supply connection detail have been omitted from the remainder of the drawings for the sake of simplicity.

II The Summer (or Adder) Connection:



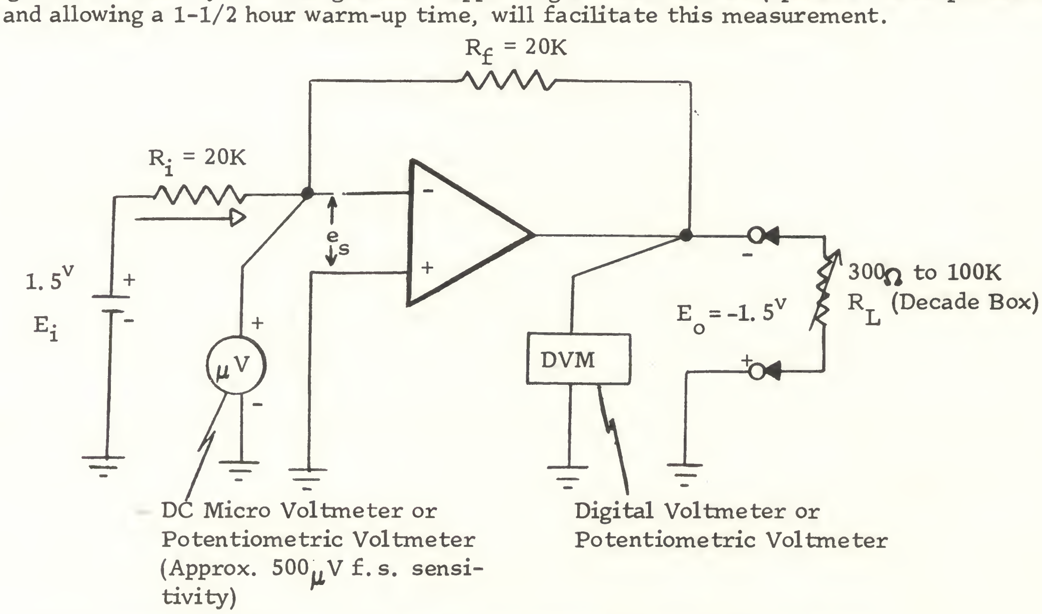
1. Approximate input currents:

$I_1 \approx \frac{E_1}{R_1} = \frac{3^V}{10K} = 300\mu A$	$I_2 \approx \frac{E_2}{R_2} = -\frac{3^V}{5K} = -600\mu A$	$I_3 \approx \frac{E_3}{R_3} = -\frac{1.5^V}{30K} = -50\mu A$

2. $I_f \approx I_1 + I_2 + I_3 = 300 - 600 - 50 = -350\mu A$
3. $E_o \approx -I_f R_f = -(-350\mu A)(20K) = +7$ Volts
4. $\boxed{E_o \approx -\left[\left(\frac{R_f}{R_1}\right)(E_1) + \left(\frac{R_f}{R_2}\right)(E_2) + \left(\frac{R_f}{R_3}\right)(E_3)\right]}$

III The Operational Amplifier may be used as a Constant Voltage Source:

NOTE: The following measurement is quite difficult to make, especially when using an operational amplifier with relatively high open loop gain (i.e., > 10,000). This problem is caused by the fact that there is a significant input offset voltage drift which also appears at the summing point (i.e., $E_{os} > \frac{E_o}{A_o}$). Minimizing the offset voltage drift caused by thermal gradients appearing across the case (operate the amplifier in a thermos bottle), and allowing a 1-1/2 hour warm-up time, will facilitate this measurement.



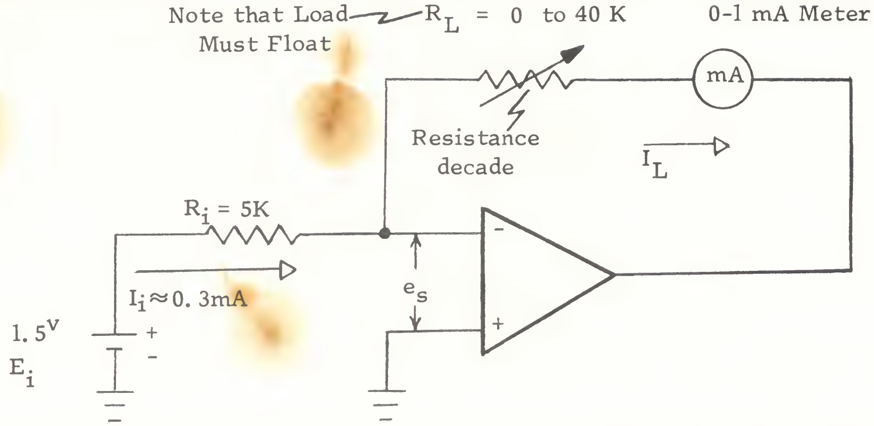
1. The output voltage, E_o, will remain almost constant as the load, R_L, is varied.
2. The input error voltage, e_s, will vary, however, because the "apparent" (or loaded) open loop gain, A_o, is a function of R_L.

$$\boxed{e_s = -\frac{E_o}{A_o} \quad \left(\begin{array}{l}\text{The approximate magnitude of } \Delta e_s \\ \text{in the above circuit is } 150\mu V\end{array}\right)}$$

3. This will cause a slight change in input current if e_s approaches the magnitude of E_i.

$$\boxed{I_i = \frac{E_i - e_s}{R_i}}$$

IV The Operational Amplifier May Be Used As A Constant Current Source:



(a) The load current, I_L (feedback current), is approximately equal to the input current, I_i. $\boxed{I_L \approx I_i \approx 0.3 \text{ mA}}$

(b) I_L will remain almost constant as R_L is varied from 2k to 33k.

(c) Above 33k ($\approx$40k) the amplifier output will go to saturation (compliance in power supply terminology).

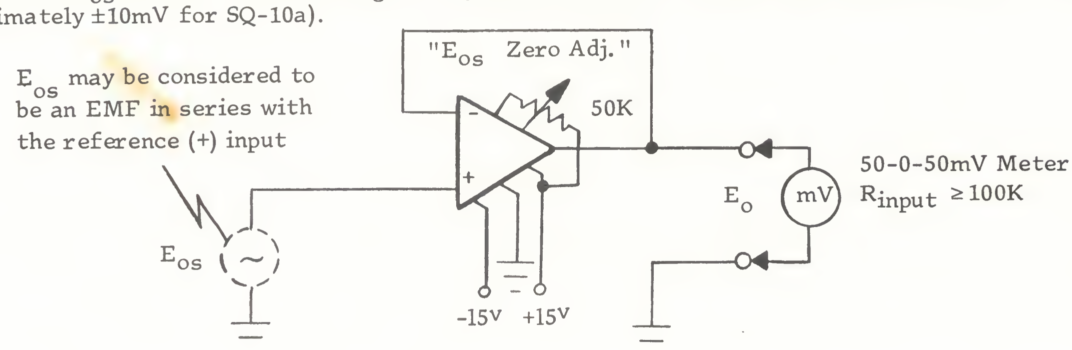
(d) Note again that the input error voltage, e_s, will increase as R_L is decreased in value. This will cause a slight decrease in I_i if e_s approaches E_i in magnitude.

$$\boxed{I_i = \frac{E_i - e_s}{R_i}}$$

(e) Therefore, $\boxed{I_L \approx \frac{E_i - e_s}{R_i}}$

V In Practice an Operational Amplifier has an Equivalent Input Offset Voltage, E_{os}.

The trim pot is used to adjust the E_{os} to zero. Normal range of adjustment for most operational amplifiers is ±3 to ±20mV (approximately ±10mV for SQ-10a).

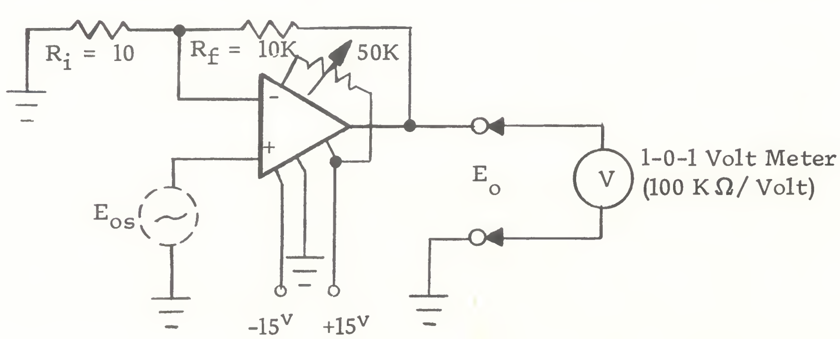


(a) Touching the case with the fingers (or otherwise unevenly heating the case) will cause significant offset voltage drifts because of the unbalance in temperature which will exist between the input pair of transistors. A temperature difference of 0.01°C between the input pair of transistors will cause nearly 25 μV of offset voltage.

(b) Changing the temperature of all portions of the case at the same time will give a measure of the offset voltage temperature coefficient, $\Delta E_{os}/\Delta T$.

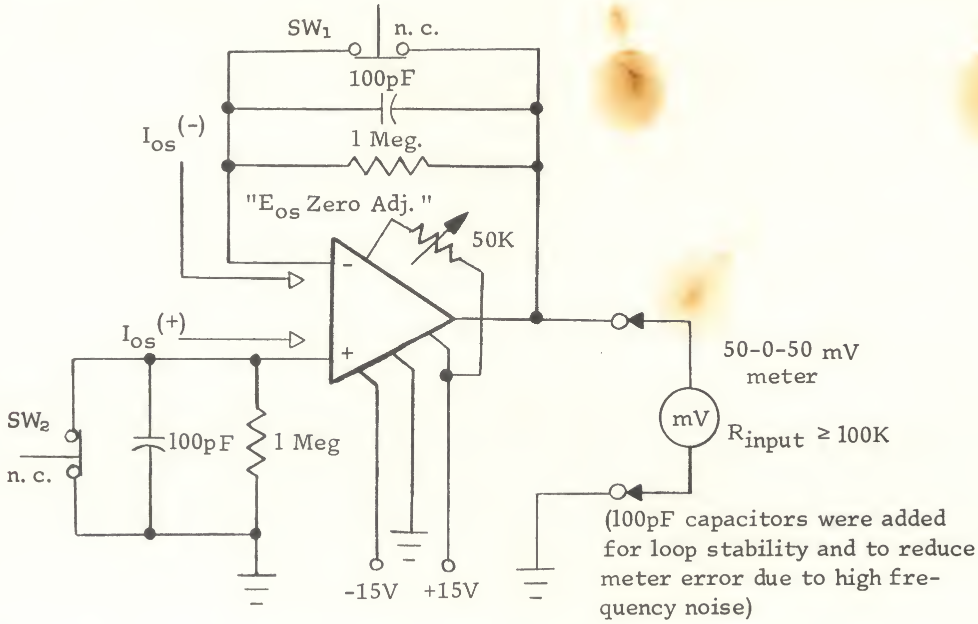
(c) $\boxed{E_o \approx E_{os}}$

(d) The E_{os} may also be measured with a voltmeter if the amplifier under test is connected for gain.



(e) $\boxed{E_o \approx (E_{os})\left(\frac{R_f}{R_i} + 1\right) \approx (E_{os})(1000)}$

VI <u>The Practical Operational Amplifier also has Input Offset Currents:</u>



(100pF capacitors were added for loop stability and to reduce meter error due to high frequency noise)

(a) With SW_1 and SW_2 normally closed, set the "E_{os} Adjust" for zero output voltage.
(b) Push SW_1 to insert the 1M Ω feedback resistor.

(c) $$\boxed{I_{os}^{(-)} = \frac{E_o}{1\ \text{Meg}\,\Omega}}$$

(d) Push SW_2 to insert the 1M Ω resistor from the reference (+) input to ground.

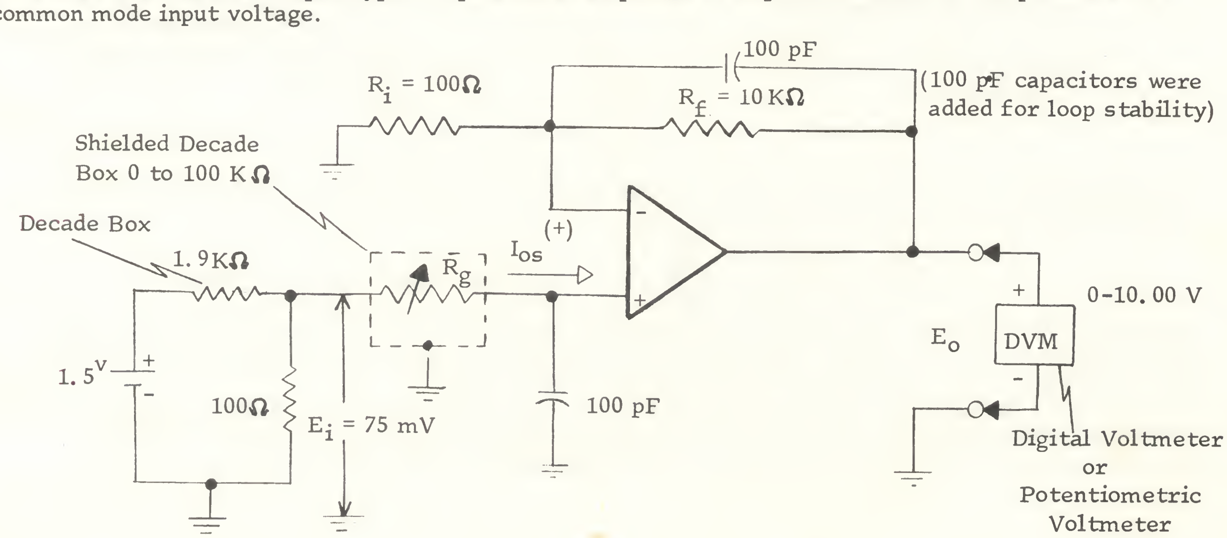
(e) $$\boxed{I_{os}^{(+)} = \frac{E_o}{1\ \text{Meg}\,\Omega}}$$

(f) Differential input offset current may be measured by pushing both buttons at the same time.

$$I_{osd} = \left| I_{os}^{(-)} - I_{os}^{(+)} \right|$$

(g) Note that this parameter is also sometimes called offset current. In that case, the input offset current from each input to ground is called <u>input bias current.</u>

VII <u>The Non-Inverting Connection</u> may be used to achieve a high input impedance with moderate to high gain. Note that a differential input type of operational amplifier is required because of the presence of a common mode input voltage.



(a) Closed loop gain, $A_{cl} = \frac{R_f}{R_i} + 1 = \frac{10K}{100} + 1 = 101$

(b) *Input resistance $= \dfrac{(R_{cm})(R_s)}{R_{cm} + R_s} = \dfrac{(10\text{ Meg})(30\text{ Meg})}{40\text{ Meg}} = 7.5\text{ Meg}\Omega$

where $R_s = (R_d)\left(\dfrac{A_o}{A_{cl}}\right) = (100K)\left(\dfrac{30,000}{101}\right) \approx 30\text{ Meg}\Omega$

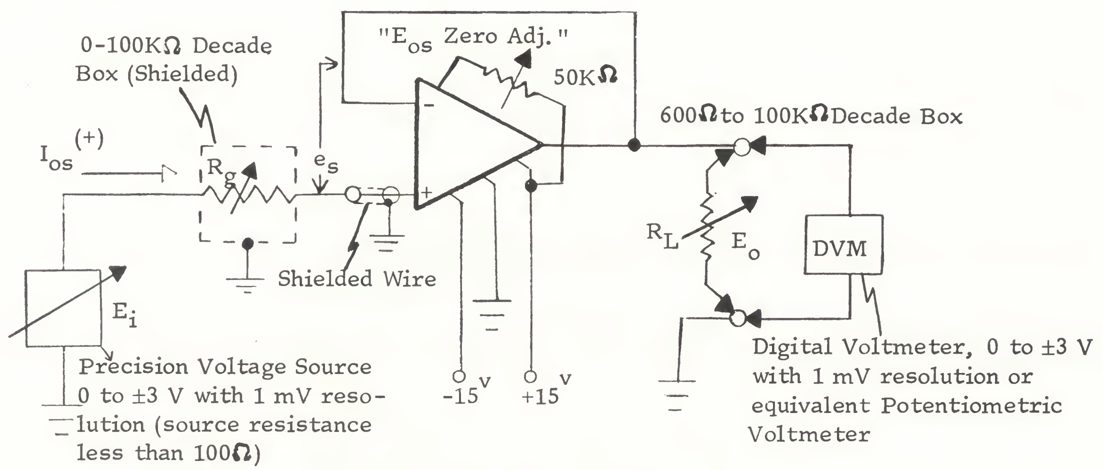
R_d = differential input resistance of amplifier

R_{cm} = common mode input resistance of amplifier

(c) It is important to note that the maximum tolerable value of R_g is generally NOT determined by the input impedance of the amplifier (which is dynamic in nature), but by the magnitude of the dc input offset current, I_{os} (+). The output voltage, E_o, will change as R_g is increased from zero. This is due to the I_{os} (+) x R_g error drop (which is amplified by A_{cl}). In the above example, the error due to the input impedance loading can be expected to be approximately 1.5%, whereas the error due to I_{os} (+) can be expected to be approximately 7%.

VIII The Voltage Follower connection may be used to transform high impedance voltage levels to low impedance voltage levels with very high transmission accuracy. Observe that a differential input type of operational amplifier is required.

NOTE: The measurement of ΔE_o due to ΔA_o (by changing R_L) is also quite difficult to make because of the E_{os} drift problem. Operating the amplifier in a thermally isolated environment and allowing about 1-1/2 hours warm-up time will facilitate this measurement.



(a) When R_g is set to zero, the input voltage, E_i, will be related to the output voltage, E_o, by the approximate equation:

$$\boxed{E_o \approx (E_i)\left[1 - \frac{1}{A_o}\right]}$$ where A_o is the "loaded" open loop gain

(b) The output voltage error will increase as the loaded resistance, R_L, is DECREASED from 100kΩ to 600Ω (with E_i set to ±3 volts). The increased current load will cause the "loaded" open loop gain, A_o, to decrease, thus increasing the input error voltage, e_s.

(c) The dc output voltage will also be in error by I_{os} (+) x R_g and may add to or subtract from E_i depending upon the direction of the input offset current of the operational amplifier. Note that I_{os} (+) is also generally a function of the common mode voltage (E_i in this case).

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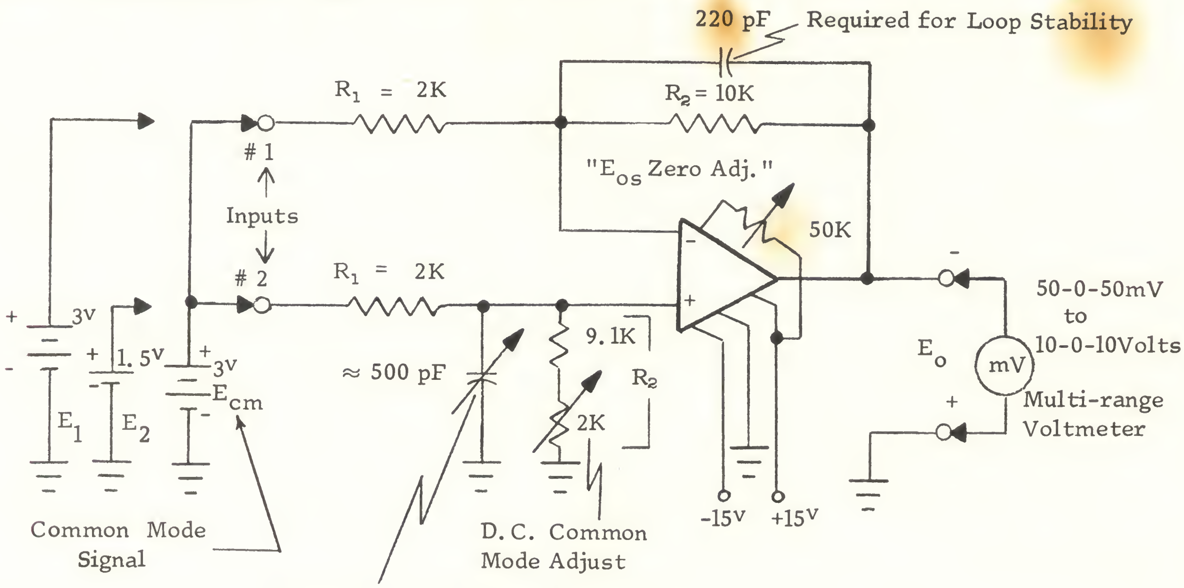
* The numerical values for R_d and R_{cm} were taken from the SQ-10a data sheet.

IX The Subtractor Connection allows an operational amplifier to be used as a differential input dc amplifier. Note that a differential input type of operational amplifier is required.



Optional A.C. Common Mode Adjust
(Capacitance is required for loop stability)

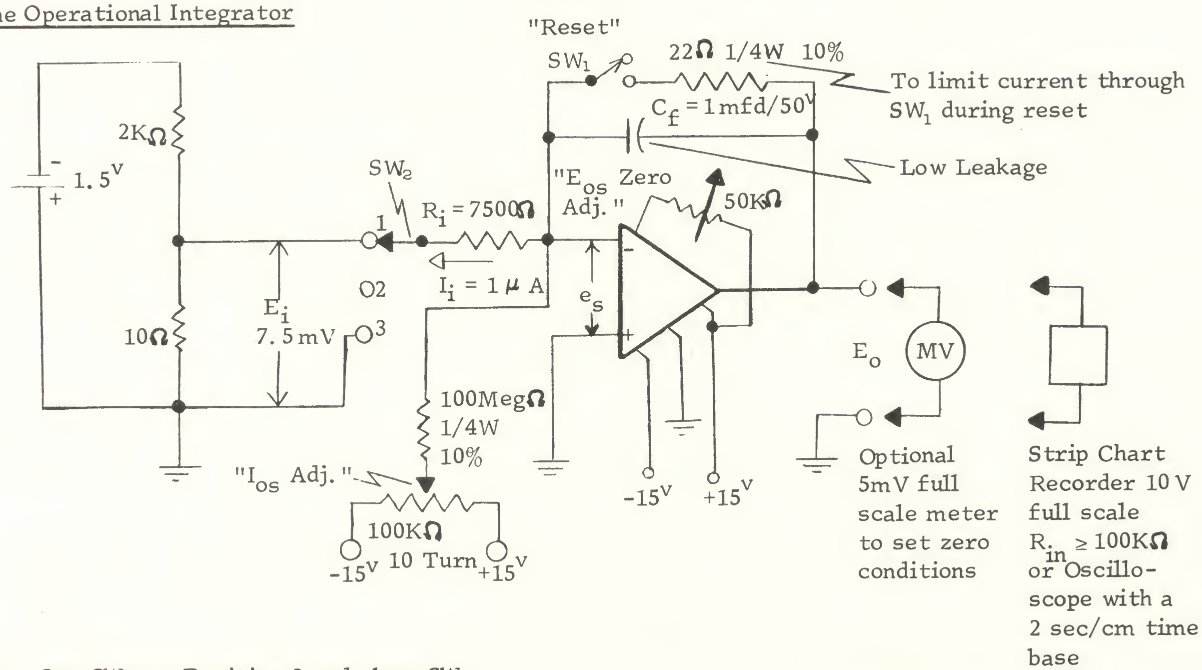
(a) With both inputs (#1 and #2) shorted to ground, set the offset voltage control for zero output on the 50mV f.s. range of the voltmeter.

(b) With a +3 volt common mode signal, adjust the 2kΩ control for a null on the 500mV f.s. range of the voltmeter.

(c) With E_1 and E_2 connected, E_o will be: $\boxed{E_o = (E_2 - E_1)\left(\frac{R_2}{R_1}\right)}$

(d) With the values shown: $\boxed{E_o = (1.5V - 3V)\left(\frac{10K}{2K}\right) = -7.5 \text{ Volts}}$

X The Operational Integrator



(a) Set SW_2 to Position 2 and close SW_1

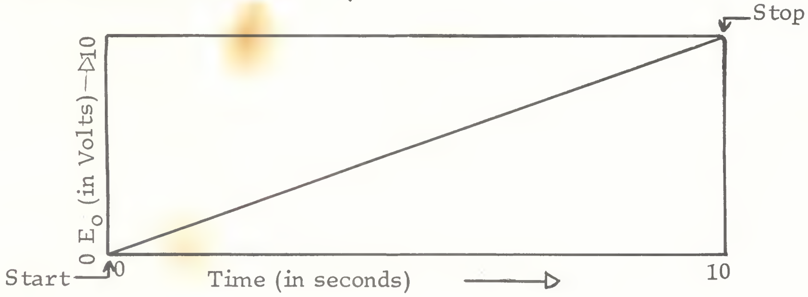
(b) Adjust "E_{os} Zero" control for zero output voltage as read on a 5mV full scale meter (or 1mV/cm dc scope or 1mV/cm recorder).

(c) Open SW_1 and turn "I_{os} Adj." until the output voltage DRIFT becomes negligible (< 1/2mV/second). This is also read on a 5mV full scale meter or equivalent.

(d) Momentarily close SW_1 to discharge C_f to zero.

(e) Switch SW_2 to Position 1 for exactly ten seconds, then return to Position 2.

(f) The strip chart recording should look like:



(g) Ideal general equation:

$$e_o = -\frac{1}{C_f}\int_o^T i_i \, dt = -\frac{1}{R_i C_f}\int_o^T e_i \, dt$$

(h) Basic dc equation:

$$\Delta E_o = -\left(\frac{E_i}{R_i C_f}\right)\left(\Delta \text{Time}\right) = -\frac{(7.5 \text{ mV})(10 \text{ sec})}{(7.5\text{K}\,\Omega)(1 \text{ mfd})} = -10 \text{ Volts}$$

(i) The integration should theoretically be linear (check recording with a straight edge) because the charging current is a linear function with respect to time. With the values chosen for this example, the actual integration linearity error should be approximately 13% of full scale. This is due to the significance of e_s with respect to the input 7.5mV signal. Good design practice therefore dictates that the input voltage, E_i, should be as large as possible.

$$\boxed{e_s = -\frac{E_o}{A_o}} \qquad \boxed{\Delta E_o = -\left[\frac{(E_i - e_s)}{R_i \; C_f}\right]\left(\Delta \text{ Time}\right) = -\left[\frac{E_i}{R_i} - \frac{E_o}{A_o R_i}\right]\left[\frac{\Delta \text{ Time}}{C_f}\right]}$$

(j) Connecting a 2kΩ load in parallel with the input to the strip chart recorder will cause a further deviation from the ideal straight line due to a further increase in e_s which resulted from a decrease in "loaded" open loop gain, A_o.

(k) Note that an incorrect adjustment of the "I_{os} Adj." control will cause the output voltage to drift during "hold."

(l) Note also, that with the "input" shorted to ground (i.e., SW_2 set to Position 3) and the "I_{os} Adj." set correctly, the output voltage will still drift during "hold" if the "E_{os} Zero Adj." is set incorrectly. This is due to an error current which is created in the input circuit and which will flow in the feedback circuit.

$$\boxed{I_{error} \approx \frac{E_{os}}{R_i}}$$

(m) If a low quality feedback capacitor is used, the effective internal resistance of the capacitor could also cause an objectionable amount of drift during "hold."

REFERENCES

1. Notes on "Working with Operational Amplifiers" by Carl M. Jackson, Electronic Products, September, 1966.
2. Nexus Research Laboratory, Inc., Application Note APP-1c, (PD-025a-1/65). "Voltage & Current Offset in Direct Coupled Transistor Operational Amplifiers."
3. Nexus Research Laboratory, Inc., Application Note APP-2, (PD-023-7/64). "Dynamic Testing of Operational Amplifiers."
4. Nexus Research Laboratory, Inc., Application Note APP-8a (PD-042a-3/65). "D.C. Amplifier, Non-Inverting."
5. Nexus Research Laboratory, Inc., Application Note APP-10a, (Notes added 7/65). "Integrator."
6. Nexus Research Laboratory, Inc., Application Note APP-11, (Notes added 7/65). "Voltage Follower."
7. Notes on Subtractor Circuit, 8/16/65.